MASTER

**DETERMINATION OF BASALT PHYSICAL
AND THERMAL PROPERTIES AT VARYING
TEMPERATURES, PRESSURES, AND
MOISTURE CONTENTS**

**First Progress Report
Fiscal Year 1979**

March 26, 1979

Prepared for Rockwell Hanford Operations,
A Prime Contractor to the U. S. Department of Energy,
Under Contract Number EY-77-C-06-1030

by:

**Excavation Engineering and
Earth Mechanics Institute**

**Colorado School of Mines
Golden, Colorado**

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Russell J. Miller
and
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1.0 ABSTRACT

This report is a summary of the rock mechanics testing done at the Earth Mechanics Institute of the Colorado School of Mines for Rockwell Hanford Operations under Subcontract SA-917. Cores were supplied from drill hole DC-6 on the Hanford Site, characterized geologically, and tested for thermal and physical properties for designing long-term underground storage of radioactive waste materials. This report presents the approved test procedures, results, and data analysis for this test series. Results indicated thermophysical properties similar to those of previously tested basalt cores from the Hanford area, but showed no significant trends; thus, generalizations are risky at this time. However, density was found to be a good guide to thermal and physical properties--higher density basalt cores showed significant improvements in physical and thermal properties.

2.0 INTRODUCTION

The concept of nuclear waste isolation, being of critical and timely importance, requires extra effort in acquiring, documenting, and presenting all information relevant to the process. The following report describes in detail the procedures, results, analyses, and conclusions relevant to the determination of the physical and thermal properties of basalt under varying ambient conditions. Also provided are all the raw data, sample control sheets, core characterization, and representative photographs of samples before and after testing. These data are available for review at the Basalt Waste Isolation Program Library located in the Columbia Bank Building, Richland, Washington.

The fiscal year 1979 (FY 79) program, of which this report is the first part, consists of testing core from deep boreholes at three locations on the Hanford Site subsequent to, and partially based on, the previous year's investigation of near-surface basalts. This report covers testing done on cores from drill hole DC-6, as shown on the Hanford Site map (Figure 2.1). In addition to presenting the results of this year's testing, this report compares the data to the previous year's results.

The intent of the program is to provide the design engineer with the basalt properties necessary for the design and analysis of a deep underground nuclear waste repository. Those properties were determined to be:

1. Uniaxial and triaxial compressive strength under various conditions of temperature, confining pressure, and moisture content;
2. Young's modulus and Poisson's ratio;
3. Strength properties of joints under various conditions of temperature, confining pressure, and moisture content;

Figure 2.1: The Hanford Area

4. Thermal transport properties--conductivity and specific heat;
5. Thermal expansion;
6. Time-dependent deformation under various conditions of load and temperature;
7. Rock hardness;
8. Thermal or mechanical anisotropy;
9. Post-failure behavior;
10. Density.

It is necessary to know the strength properties of intact and jointed core for specifying opening geometry, pillar sizes, support requirements, and excavation methods. Young's modulus and Poisson's ratio are required for determining stress distributions and subsidence potential. Thermal properties are needed, as the canisters of waste material will heat the surrounding rock causing changes in stress, mechanical properties, and possibly long-term behavior of the repository. Time-dependent deformation, or creep, although expected to be minimal, could have an impact on subsidence, local fracturing, or the long-term stability of an opening. Rock hardness has implications in the areas of excavation methods and potential over break or blast damage into the walls of openings. If anisotropy exists, it is critical to any modeling effort to identify its prevalence and magnitude. Post-failure analysis identifies the remaining support capability of a pillar that, for some reason, may have failed. Failed pillars can still carry significant loads and can play an important part in support in a large areal underground opening. Density was determined for all samples, as a good correlation was previously found between density and many physical and thermal properties of basalt. And, as mentioned, the canisters of nuclear waste will heat the surrounding basalt, so it is important that the above properties be determined over the temperature range likely to be encountered.

Following is a presentation of the procedures, results, and discussion relevant to the physical and thermal properties discussed above.

3.0 TEST RESULTS

3.1 CHARACTERIZATION OF CORE SAMPLES

3.1.1 Procedures

The characterization of all core was accomplished through the following procedures:

1. Record date of receipt and sample designation of core, including locality, formation, drill hole number, and footage interval;
2. Photograph core in box as received using color Polaroid and Kodachrome film;
3. Rearrange in proper position any segments of core which have been jostled out of position in transit;
4. Spray core with water and wipe off drilling sludge for visual inspection;
5. Hand-lens description and identification of textural, structural, and mineralogical features of the core;
6. Binocular microscopic examination of features not readily discernible with hand lenses;
7. Preparation and microscopic petrographic analysis of selected thin sections of core to evaluate and amplify observations made megascopically and with the binocular microscope;
8. Integrate hand lens, binocular microscopic, and thin section microscopic data in final lithologic description of the core;
9. Close-up photography of selected segments of core to illustrate important lithologic features and variations;
10. Preparation of graphic log of core in 2 inch (in.) equals 1 foot (ft.) scale which describes in detail the fractures which are

present, as well as the mineralogy, texture fabric, and interflow features. Also, the location of all thin sections, test samples, and close-up photographs will be noted on the log.

In addition, to help define the effects of geologic structure upon basalt physical properties, those samples showing non-typical behavior and several representative samples were carefully characterized with respect to mineralogy and rock structure.

Based on the geologic characterization, areas within a line of core were identified for testing. The criterion for selecting an area for testing was that it represents a distinct group of geologic characteristics and that test specimens can be obtained from that area. In addition, a procedure was followed to assure, to the greatest extent possible, that the interrelated tests be performed on geologically similar samples. Thus, each group of tests is on samples from the same area of the core to maximize the validity of correlations between the various physical and thermal properties. Several of the tests are conducive to using the same sample and this was done when possible. Since variations in rock fabric, jointing, and mineralogy are likely to occur along the length of the core, each sample was described in detail and variations in physical or thermal behavior were correlated to the sample geologic characteristics.

Once a section of core was selected for testing, its dimensions were marked for cutting and a sample number, drill hole number, and a precise location were marked on it in indelible ink. It was at this point that the use of a core control sheet was initiated. On the sheet, the core was identified as to the test to be performed, sample number, drill hole, location, and core box number. The core was carefully described in terms of its geologic characteristics and then sent for preparation.

Following core preparation, the dimensions and quality of preparation were thoroughly checked before being sent for testing. For each test, there was a check-off procedure to assure correct test procedure and recording of data. Each test was observed and checked by the appropriate supervisor. Any calculations required were then performed and checked. If characteristics of the sample or procedure were believed to affect the results, this was noted on the control sheet. Finally, the data were collected and organized with a duplicate copy made and stored separately. Responsible individuals are required to sign off and each operation is monitored by a separate individual. A copy of the control sheet was maintained for each area of responsibility by the person in charge. This provides additional control and allows tracing and review of the testing procedure. In addition, numerous photographs were taken of the core at various stages providing a further control on sample identification.

3.1.2 Initial Sample Log

This section contains the graphic log of the core as received, on a scale of 2 in. equals 1 ft. of core. Rockwell core box numbers, footages, and general descriptions of the cores are included, as well as the locations of the test samples. The sample designations are abbreviated as follows:

U : uniaxial test specimen;
TX : triaxial test specimen;
TJ : jointed triaxial test specimen;
PF : post-failure test specimen;
UC : uniaxial creep test specimen;
TS : thin section specimen;
CP : specific heat test specimen;
K : thermal conductivity test specimen;

KP: Thermal conductivity test specimen (recored perpendicular to
core axis);

XP: thermal expansion test specimen.

Series A replacement cores

<u>Diagram</u>	<u>Footage</u>	<u>Description</u>
3039.7 3040.9	Porous rock
3048.7 3049.9	Porous conglomerate
3132.5 3133.0	Jointed but solid
3144.5	Little grey rock
3144.5 3145.3	Solid basalt
3156.7 3157.2	Jointed
3166.6 3167.3	Good joint for testing

DiagramFootageDescription

3173.0
3173.4

Solid

3175.9
3176.5

Solid Rock

3258.6
3259.9

Porous and
white fill

Box
Nbr.

Diagram

Description

324

Porous--white fill

340

Jointed

348

Joints both parallel and perpendicular to core axis

335

339

340

340

Closed joints parallel to core axis

349

One side chipped out completely

348

349

Vesiculated, closed joints
(pretty crystals)

All cores 1.87" Ø

Box Nbr.	Diagram	Description
349		Porous, white fill
324		Porous aggregation
326		Porous aggregate, white fill
325		Aggregate, vesicles, not 2.0 ft.
326		Solid aggregate, chipped
334		Hard, chipped, jointed parallel to core axis < 1 ft.
334		Little gray rock
334		Extensive jointing parallel to core axis
339		Smooth, clean, few joints
336		Hard, black, a few joints parallel to core axis

Box
Nbr.DiagramDescription

336

Hard, black, some jointing

338

Up-axis arrows erased

337

Hard basalt - undercored
sample perpendicular to
core axis has been
removed 10/26/78

3.1.3 Initial Characterization

Series A - Lithologic Log

Drill Hole DC-6

Formation: Umtanum

<u>Box</u>	<u>Footage</u>	<u>Description</u>
324 Flow Top	3036.1- 3037	Basalt; dark gray to black; microcrystalline, non-porphyr- itic; highly vesicular, with irregular vesicles up to .8 x 1.6 in. (2 x 4 centimeters [cm.]); vesicles lined with <.04 in. (1 millimeter [mm.]) coating of green mont- morillonite and white zeolite (?); many vesicles elongate approximately perpendicular to core axis and probably approximately parallel to flow layering; locally swarms of vesicles swirling nearly parallel to core axis
	3036.1	Fresh, irregular fracture 80° to core axis
	3036.7- 3036.8	Irregular fracture 65° to core axis partially coated with montmorillonite and zeolite (?)
	3036.8- 3037	Irregular, conchoidal fractures at various angles to core axis tightly sealed with above minerals
324 Flow Top	3039.7- 3040.9	Basalt; dark gray; microcrystalline, non-porphyr- itic; breccia of vesiculated fragments up to 2 in. (5 cm.) vesicles lined and breccia fragments cemented with white zeolite (?) and montmorillonite; considerable porosity
324 Flow	3043- 3044	Primary lithology as above, however, entire interval is flow breccia with vesiculated fragments up to 2 in. (5 cm.) breccia fragments cemented and vesicles lined with zeolite (?)
325 Flow Top	3048.7- 3049.7	Essentially identical to above, with slightly more zeolite (?) and montmorillonite
325 Flow Top	3051.6- 3053.6	Flow breccia as in interval 3043-3044
	3051.9- 3052	Highly irregular open fracture approximately perpendicular to core axis
	3053.5 3053.6	Many vesicles filled with green montmorillonite
326 Flow Top	3054.8- 3055.3	Flow breccia similar to interval 3043-3044

Box Nbr.	Footage	Description
326 Flow Top	3058.3 3058.9	Basalt; greenish-gray; microcrystalline, non-porphyritic; clusters of small vesicles up to .04 in. (1 mm.), coated and partly filled with green montmorillonite; greenish color of rock suggests microcrystalline chloritic alteration throughout
	3058.3- 3058.4	Planar fractures 40° and 50° to core axis coated with montmorillonite and lesser zeolite (?)
	3058.3- 3058.55	Curvilinear fracture approximately parallel to core axis filled with >.04 in. (1 mm.) of montmorillonite
	3058.45- 3058.65	Curvilinear fracture approximately 40° to core axis coated as above
	3058.75 3058.9	Irregular fracture approximately parallel to core axis filled with >.04 in. (1 mm.) of zeolite
	3058.9	Hackly, planar fracture 60° to core axis coated as above
334 Central Flow	3127.3- 3127.5	Basalt; black; massive; dense; hard; brittle; aphanitic, microcrystalline, non-porphyritic; faint suggestion of microphenocrysts, probably of plagioclase; very fresh rock with only hairline alteration adjacent to tight fractures
	3127.3- 3127.45	Irregular, curvilinear, tight fracture approximately 20° to core axis with thin film of montmorillonite
	3127.3- 3127.5	Tight, planar, hairline fracture parallel to core axis sealed with film of montmorillonite
334 Central Flow	3128.5- 3129.5	Basalt as in interval 3127.3-3127.5; occasional, small vesicles and amygdules; scalloped, sub-planar fracture parallel to core axis filled with <.04 in. (1 mm.) of montmorillonite; few tight, irregular, hairline fractures at various angles to core axis terminate against fracture parallel to core axis
334 Central Flow	3131- 3132	Basalt as in interval 3127.3-3-3127.5; several scalloped fractures sub-parallel to core axis cemented with up to .04 in. (1 mm.) of montmorillonite and silica mineral, probably chalcedony; several, irregular smaller fractures at various angles to core axis some of which are hairline fractures, other cemented as above; all fractures are potential surfaces of failure during physical properties testing
335 Central Flow	3132.5- 3133.0	Basalt; black; massive; dense; hard; brittle; aphanitic; microcrystalline; non-porphyritic; few microphenocrysts of plagioclase; tight, irregular, scalloped fractures at various angles to core axis filled with up to .04 in. (1 mm.) of montmorillonite and zeolite (?)

<u>Box Nbr.</u>	<u>Footage</u>	<u>Description</u>
334 Central Flow	3138.1- 3139.4	Basalt as in interval 3127.3-3127.5; several tight fractures at various angles to core axis and cemented as above
	3138.5- 3138.9	Irregular, scalloped fracture approximately 15° to core axis, open and coated with montmorillonite
336 Central Flow	3141.5- 3142.5	Basalt as in interval 3127.3-3127.5; numerous, sealed fractures thinly coated as above at various angles to core axis
336 Central Flow	3143- 3144	As in interval 3127.3-3127.5
336 Central Flow	3144.5- 3145.3	Lithology as above; fractures as above; several irregular vesicles up to .8 in. (2 cm.) filled with montmorillonite and chalcedony
337 Central Flow	3147.6- 3149	As in interval 3127.3-3127.5
338 Central Flow	3156.7- 3157.2	Lithology and fractures as above; fractures tight and coated only with montmorillonite; minor vesicles up to .1 in. (3 mm.) coated and partly filled with montmorillonite
338 Central Flow	3163.6- 3165.3	Ditto; scalloped, irregular fracture approximately parallel to core axis filled as above
339 Central Flow	3165.8- 3166.6	As in interval 3127.3-3127.5
339 Central Flow	3166.6- 3167.0	Ditto; fractures approximately parallel to core axis contain chalcedony with montmorillonite
339 Central Flow	3168.7- 3169.2	As in interval 3127.3-3127.5
339 Central Flow	3173.0- 3173.4	As in interval 3127.3-3127.5
340 Central Flow	3175.9- 3176.5	As in interval 3127.3-3127.5
340 Central Flow	3179.5- 3180.2	As in interval 3127.3-3127.5

Box Nbr.	Footage	Description
340 Central Flow	3182.5- 3183.0	As in interval 3127.3-3127.5
340 Central Flow	3183.3- 3184	As in interval 3127.3-3127.5
348 Flow Bottom	3248.5- 3248.8	As in interval 3127.3-3127.5
348 Flow Bottom	3251- 3253	Basalt as above showing wavy, discontinuous, slightly greenish mottling approximately perpendicular to core axis and probably representing flow layering; less fractured than above
	3252.2- 3253	Basalt, light gray, mottled as above; mottling is probably patchy secondary, green montmorillonite
349 Flow Bottom	3256- 3256.3	As in interval 3251-3253
340 Flow Bottom	3256.8- 3257.6	Basalt as above with moderately abundant vesicles and amygdules up to 1.6 in. (4 cm.) elongate and flattened approximately perpendicular to core axis and parallel flow layering; amygdules are filled with soft, earthy white mineral, icy crystalline zeolite (?), and green montmorillonite; some vesicles lined with black manganese oxide coating
	3257.25- 3257.6	Swarms of smaller vesicles and amygdules, <.04-12 in. (1-3 mm.) swirling up to 45° to core axis
349 Flow Bottom	3258.6- 3259.9	Basal flow breccia identical in lithology to interval 3261.1-3262
340 Flow Bottom	3261.1- 3262	Basal flow breccia with angular fragments up to 2.4 in. (6 cm.) of microvesicular, prophyritic-aphanitic basalt with white plagioclase phenocrysts .04 in. (1 mm.) long; vesicles in clasts and matrix of breccia partially filled and cemented with white zeolite (?) and green montmorillonite

3.2 MEASUREMENT OF STRENGTH PROPERTIES OF INTACT CORE UNDER VARYING AMBIENT CONDITIONS

3.2.1 Apparatus

The loading device used is a MTS Systems 1-million pound capacity "stiff" testing machine which is servo-controlled for either loading rate or deformation rate control. In addition, the unit can interface directly with a PDP-11/05 computer for data analysis or testing program control.

For room-temperature testing, the confining pressure is applied to the specimen by a triaxial test chamber manufactured by Terrametrics, Inc. The hydraulic pressure to this cell is also servo-controlled, assuring a constant level of confining pressure throughout the test.

Elevated-temperature triaxial testing is done in the Colorado School of Mines' Earth Mechanics Institute (EMI) custom-fabricated, high-temperature triaxial cell. This uses servo-controlled nitrogen pressure, with an internal, 3-zone 6-kilowatt resistance heater, which allows control of temperatures up to 500 degrees centigrade (°C).

Hardened steel platens were used conforming to American Society for Testing Materials (ASTM) requirements as set forth in ASTM Standard D-2938. Spherical seats of the required size were employed for all tests.

3.2.2 Test Specimens

Test specimens were right circular cylinders within tolerances specified in ASTM D-2938. The length is as close to two times the diameter as possible (except that shorter samples are required in the highly fractured sets of core tested under this contract). Exception is also taken to the ASTM D-2938 requirement for NX core (2-1/8-in. diameter), as most of the core for this contract was smaller in diameter (1-7/8-in.). The samples were oven dried overnight at 90°C where required. The diameter and length were

determined to within 0.01 in. and the weight measured to 0.1 gram. For the tests at high temperatures, the samples were heated overnight at the desired temperature prior to testing.

3.2.3 Procedures

Before each series of tests, the calibration cylinder is loaded in the testing machine, and calibration and linearity checked. For a room-temperature triaxial test, the sample was centered in the membrane of the hydraulic triaxial cell, the lower platen was inserted at the bottom of the cell, and the upper platen at the top of the cell. The unit was then centered in the testing machine and the spherical seat placed on the upper platen. As a slight preload is applied to the sample, the spherical seat was adjusted to assure uniform seating. The desired confining pressure was then applied to the sample and a constant deformation rate was programmed into the testing machine to induce failure in approximately 10 minutes. At every 5 to 10 thousand pounds of incremental applied load, the load was held temporarily constant and all strains recorded. The load-total deformation behavior was recorded on a chart recorder for a permanent record.

High-temperature triaxial tests were conducted similarly, but with more equipment. The sample to be tested was placed in an aluminum can in a stainless steel sample holder, and heated in an oven to bring it to the desired (test) temperature. The sample in the holder was then loaded into the heating chamber of the high-temperature cell, the deflection probes positioned, outgas vent connected, and controller thermocouples placed. Then

the cell was sealed, placed in the machine, preloaded, and the desired gas pressure selected on the pressure controller. A controlled deformation rate was programmed into the testing machine to induce failure in about 10 minutes. Again, the load, radial deformation, and axial deformation behavior are recorded on a chart for a permanent record.

Uniaxial (strain rate) tests were conducted similarly, but much more simply due to the lack of elastic property measurements. If saturated, the sample was placed in the testing frame in a Ziploc bag to keep the water from being driven off during the test. If heated, the sample was removed from the oven, wrapped in a flexible ceramic insulation sheath, and placed in the test frame. A spherical seat was lubricated and centered atop the sample, and a variable deformation rate--calculated to be from 1000 to 100,000 microstrains in the sample per minute--was programmed into the machine, and the sample loaded to failure. In the case of very hot samples (300-500°C), the spherical seat was also heated in the oven to minimize sample heat losses. Again, the load-total deformation behavior was recorded via chart recorder and included with the final report.

3.2.4 Calculation

The compressive strength of the sample was calculated by dividing the maximum load carried by the sample by the cross-sectional area of the sample. Where samples shorter than 2 times the diameter had to be tested, their compressive strength was adjusted to that for a 2:1 specimen by using the equation:

$$C = C_a / 0.88 + 0.24 (b/h) \quad (1)$$

where

C = computed compressive strength of an equivalent L/D = 2 specimen;

C_a = measured compressive strength of the specimen tested;

b = test core diameter;

h = test core height.

3.2.5 Test Results

Three sets of strength tests were done on the intact cores: triaxial, varying confining pressure; triaxial, varying sample temperature; and uniaxial, varying sample temperature, water saturation, and strain rate. Triaxial tests with varying confining pressure were conducted at room temperatures, with 3 repetitions each at 50 pounds per square inch gauge pressure (psig) with fresh samples, 50 psig with samples heated to 500°C and cooled, 2500, 5000, and 7500 psig. Triaxial tests at varying sample temperatures were conducted at 50 psig nitrogen pressure, with 3 repetitions each at 20°C water saturated, 20°C oven-dried, 150, 300, and 500°C. Uniaxial tests were conducted at 4 strain rates: 1000, 10,000, 25,000 and 100,000 micro-strains per minute; at 5 temperature conditions each: 20°C water saturated, 20°C oven-dried, 150, 300, and 500°C.

Table 3.1 presents the results of the varying confining pressure triaxial tests. Table 3.2 presents the varying temperature triaxial results. Table 3.3 shows the results of the uniaxial strain rate tests. In all cases, the results are presented in order of increasing depth.

3.2.6 Test Data Analysis

The first trend to be noticed was that the higher segment of the core (3036.3 to 3058.7 ft.) from the upper portions of the flow showed significantly lower values of strength and Young's modulus than the remainder

TABLE 3.1

STRENGTH PROPERTIES OF INTACT CORE AS A FUNCTION OF CONFINING PRESSURE

<u>DEPTH (ft)</u>	<u>SAMPLE NUMBER</u>	<u>DENSITY (gm/cc)</u>	<u>TEST CONDITIONS</u>	<u>FAILURE STRESS (ksi)</u>	<u>YOUNG'S MODULUS (10⁶psi)</u>	<u>POISSON'S RATIO</u>
3055.0	TX 7	2.10	2500 psi	27.89	0.91	.246
3128.7	TX 9	2.81	7500 psi	98.77	9.96	.186
3131.3	TX 10	2.76	hot/cooled	37.43	10.17	.474
3139.1	TX 12	2.79	5000 psi	21.01	4.89	.347
3143.8	TX 15	2.79	2500 psi	29.90	5.25	.185
3148.0	TX 16	2.81	7500 psi	84.99	11.02	.240
3166.1	TX 20	2.80	hot/cooled	52.98	7.84	.162
3168.8	TX 21	2.75	hot/cooled	26.94	6.49	.144
3180.0	TX 22	2.78	2500 psi	83.78	12.14	.288
3183.7	TX 23	2.77	50 psi	51.99	ND	ND
3248.7	TX 24	2.77	7500 psi	127.36	12.27	.290
3251.4	TX 25	2.82	50 psi	66.79	12.69	.246
3251.9	TX 26	2.82	50 psi	50.62	14.12	.297
3257.3	TX 27	2.49	5000 psi	42.76	1.47	.212
3261.6	TX 30	2.34	5000 psi	31.99	2.66	.162
MEAN VALUES AND		2.77	hot/cool	39.12	8.17	.260
STANDARD DEVIATION		±.03		±13.10	±1.86	±.186
TIONS AT EACH		2.80	50 psi	56.47	13.40	.272
PRESSURE		±.03		± 8.97	± 1.01	±.036
		2.56	2500 psi	47.19	6.10	.240
		±.40		±31.70	± 5.66	±.052
		2.54	5000 psi	31.92	3.01	.240
		±.23		±10.88	± 1.74	±.096
		2.80	7500 psi	103.71	11.08	.239
		±.02		±21.61	± 1.16	±.052

TABLE 3.2

STRENGTH PROPERTIES OF INTACT CORE AS A FUNCTION OF TEMPERATURE

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(gm/cc)</u>	<u>TEST</u> <u>CONDITIONS</u>	<u>FAILURE</u> <u>STRESS</u> <u>(ksi)</u>	<u>YOUNG'S</u> <u>MODULUS</u> <u>(10⁶psi)</u>	<u>POISSON'S</u> <u>RATIO</u>
3036.3	TX 1	2.09	150°C	7.54	2.78	.366
3043.8	TX 3	2.08	150°C	6.01	1.32	.483
3051.7	TX 4	2.15	150°C	6.46	2.38	.191
3052.7	TX 5	2.11	300°C	9.31	2.53	.272
3053.0	TX 6	2.09	300°C	10.18	2.12	.330
3053.2	TX 31	2.11	500°C	11.55	2.93	.328
3058.7	TX 8	2.49	20°C dry	13.84	3.80	.581
3142.2	TX 13	2.77	20°C dry	37.87	18.27	.309
3148.9	TX 17	2.78	20°C wet	58.56	22.60	.462
3163.7	TX 18	2.79	20°C wet	46.65	11.40	.193
3164.5	TX 19	2.79	20°C wet	17.98	22.66	.504
3166.3	TX 32	2.80	500°C	18.25	4.06	.160
3179.8	TX 33	2.78	500°C	22.92	4.63	.115
3251.7	TX 34	2.82	300°C	28.01	3.58	.299
3261.2	TX 29	2.36	20°C dry	17.21	3.18	.216
MEAN VALUES AND		2.79	20°C wet	41.06	18.89	.386
STANDARD DEVIATION		±.01		±20.86	± 6.48	±.169
TIONS AT EACH		2.54	20°C dry	22.97	8.42	.369
TEMPERATURE		±.21		±13.01	± 8.54	±.190
		2.11	150°C	6.67	2.16	.347
		±.04		± 0.79	± 0.75	±.147
		2.34	300°C	15.83	2.74	.300
		±.42		±10.55	± .75	±.029
		2.56	500°C	17.57	3.87	.201
		±.39		± 5.72	± .87	±.112

TABLE 3.3

UNCONFINED STRENGTHS AS A FUNCTION OF STRAIN RATE AND TEMPERATURE

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(gm/cm³)</u>	<u>TEMP</u> <u>(°C)</u>	<u>STRAIN RATE</u> <u>(με /min)</u>	<u>FAILURE STRESS</u> <u>(ksi)</u>
3036.5	U 2	1.91	150	5000	6.63
3036.9	U 1	1.99	20-dry	1000	2.98
3043.8	U 3	2.11	150	25000	12.70
3052.5	U 4	2.21	150	100000	12.82
3053.4	U 5	2.11	150	10000	11.20
3055.2	U 6	2.04	20-wet	10000	4.33
3129.1	U 7	2.75	300	25000	27.19
3131.7	U 8	2.76	300	10000	21.86
3139.3	U 21	2.79	20-wet	100000	23.82
3141.6	U 10	2.80	20-dry	200000	35.08
3147.7	U 11	2.80	20-dry	100000	34.73
3148.5	U 12	2.80	20-dry	25000	52.38
3148.7	U 22	2.80	20-wet	1000	26.98
3164.1	U 13	2.80	500	1000	14.80
3165.0	U 14	2.81	500	10000	33.64
3166.5	U 15	2.80	300	100000	26.28
3169.1	U 16	2.70	500	100000	11.30
3179.6	U 17	2.77	500	25000	35.18
3183.4	U 18	2.79	300	1000	7.26
3252.1	U 19	2.83	20-dry	10000	69.98
3261.8	U 20	2.38	20-wet	25000	10.18

TABLE 3.3 (Cont'd)

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(gm/cm³)</u>	<u>TEMP</u> <u>(°C)</u>	<u>STRAIN RATE</u> <u>(μE /min)</u>	<u>FAILURE STRESS</u> <u>(ksi)</u>
MEAN VALUES AND STANDARD DEVI- ATIONS AT EACH CONDITION		2.60 ±.40	-	1000	13.00 ±10.52
		2.51 ±.40	-	10000	28.20 ±25.86
		2.56 ±.31	-	25000	27.53 ±17.30
		2.66 ±.26	-	100000	21.79 ± 9.78
		2.50 ±.37	20-wet	-	16.33 ±10.82
		2.64 ±.37	20-dry	-	39.03 ±24.85
		2.09 ±.13	150	-	10.84 ± 2.90
		2.78 ±.02	300	-	20.65 ± 9.22
		2.77 ±.05	500	-	23.73 ±12.43

of the core. This would be expected and agrees with trends found last year for near-surface basalts. This area of the core is characterized by various degrees of vesicularization, alteration, and clastic appearance. Noticeable changes occur in the color and texture of much of the material from this upper zone when heated to high temperatures—it basically turns yellow and grainy.

Other than the observed changes in appearance of the samples, the effect of temperature seems to be about a 50 percent decrease in strength and Young's modulus with heating to 500°C, as seen in Figure 3.1. Poisson's ratio appears to decrease with temperature, but again, more data are needed to smooth out the scatter in the results and verify these conclusions.

As can also be seen from Figure 3.1, the saturated samples are grouped toward the high end of the strengths at 20°C. This may be a real effect, as this grouping does not occur in the modulus and Poisson's ratio results. More results will be necessary before that observation can be confirmed. If only the dried samples are considered, one might not have concluded a temperature effect on strength.

Heating and cooling the samples appeared to shift their strengths downward from the dried samples, but they remain at about the overall average. Again, more data will be required to confirm any effect.

Young's modulus and Poisson's ratio are shown versus temperature in Figures 3.2 and 3.3. There appears to be a temperature effect in heating the samples above 20°C. However, two factors should be considered in evaluating this trend: first, the samples at 150°C are from the upper flow; and, second, strain gages were used at 20°C, and cantilever probes used at all other temperatures to determine sample deformations. The results, however, are quite consistent.

Moisture content and heating and cooling appear to have an indeterminate effect on Young's modulus.

Figure 3.1: Failure Stress Versus Temperature

Fig 3.2: Young's Modulus Versus Temperature

Figure 3.3: Poisson's Ratio Versus Temperature

Figure 3.3 displays a fairly monotonic decrease in Poisson's ratio with increasing temperature. The standard deviations and lack of a similar trend in Young's modulus, however, make one reluctant to recognize an effect. In addition, the radial deformation probes are the most sensitive-to-temperature part of the measurement system.

Again, moisture content and heating and cooling have no identifiable effect on Poisson's ratio.

From previous experience, confining pressure is known to have a very significant effect on the compressive strength of basalt. It was, therefore, a surprise when the results shown in Figure 3.4 were plotted. Even with the standard deviations shown, one could conclude there was no effect of confining pressures up to 5000 psi. There is, however, a near doubling of strength at 7500 psi. These results remain somewhat of a question, but it is hoped that future tests will clarify the situation.

Mohr's envelope analysis was done at three depths, where the data were thought to warrant it. The results are presented in Figures 3.5, 3.6, and 3.7. It is notable that, even with the large amounts of scatter in the measured data, characteristics of Mohr's envelopes were able to be plotted with consistent friction angles ($36-44^\circ$) in all three.

Strain rate effects on sample strength can be quite significant for some rocks. The results of the strain rate tests for the first series of basalt samples is shown in Figure 3.8. There are certainly insufficient data to warrant a definitive conclusion on strain rate effects on basalt, but one might qualitatively observe a trend toward increasing failure stress with increasing strain rate. Again, it can be noted that the samples from the upper flow area are significantly weaker.

RHO-BWI-C-50

Figure 3.4: Failure Stress Versus Confining Pressure

Figure 3.5: Mohr's Envelope - Triaxial Results 3055' - 3059'

Figure 3.6: Mohr's Envelope - Triaxial Results 3129' - 3148'

Figure 3.7: Mohr's Envelope - Triaxial Results 3249' - 3262'

Figure 3.8: Failure Stress Versus Strain Rate

3.3 MEASUREMENT OF STRENGTH PROPERTIES OF JOINTED CORE UNDER VARYING AMBIENT CONDITIONS

3.3.1 Apparatus

Joint testing was accomplished using the existing high-temperature triaxial cell, Terrametrics' hydraulic triaxial cells, and the MTS stiff testing machine.

3.3.2 Test Specimens

Test specimens were right circular cylinders within tolerances specified in ASTM D-2938. The length was as close to 2 times the diameter as possible (except that shorter samples were used in these highly fractured sets of core). Exception is also taken to the ASTM D-2938 requirement for NX core (2-1/8-in. diameter), as most of the core for this contract was smaller in diameter (1-7/8-in.). The samples were oven dried overnight at 90°C where required. The diameter and length were determined to within 0.01 in. and the weight measured to 0.1 gram. For the tests at high temperatures, the samples were heated overnight at the desired temperature prior to testing. Samples were chosen such that there was an apparent joint at a critical angle through the sample.

3.3.3 Procedures

Compression tests on jointed samples were performed at varying ranges of temperature, confining pressure, and moisture content to determine their effect on strength and deformation properties of jointed basalt.

Tests were performed on 5 jointed samples, 2 of which were saturated prior to testing, at 4 temperatures (20, 150, 300, and 500°C), with each joint being tested sequentially at each temperature. Also, 5 jointed samples, 2 of which were saturated prior to testing, were tested at 4 confining pressures (1000, 2000, 3000, and 5000 psi). Each sample was loaded to failure

for a given confining pressure. After the failure load had been determined, the confining pressure was increased to the next level and the sample loading continued to the next failure.

The following properties were determined during the compression tests:

1. Compressive strength;
2. Cohesion;
3. Friction angle of joint surface.

Following testing, the joint infilling material was characterized in detail.

3.3.4 Calculation

The compressive strength of the joint at each failure was calculated from:

$$\sigma_{ax} = \frac{F_f}{A} \quad (2)$$

where

σ_{ax} = axial stress at failure;

F_f = failure load;

A = sample cross-sectional area.

The friction angle of the joint surface was calculated for each slip after the first from:

$$\tan-\phi = \frac{\tau_n}{\sigma_n} \quad (3)$$

with

$$\tau_n = \text{joint shearing stress} = (\sigma_{ax} - \sigma_c) \sin \theta \cos \theta ; \quad (4)$$

$$\sigma_n = \text{joint normal stress} = \sigma_{ax} \sin^2 \theta + \sigma_c \cos^2 \theta ; \quad (5)$$

where

ϕ = friction angle of joint;

σ_{ax} = axial failure stress;

σ_c = confining pressure;

θ = joint slip angle, measured from vertical.

The inherent cohesion of the joint is calculated from the first slip of the joint using the formula:

$$\tau_i = \tau_n - F \sigma_n \quad (6)$$

where

τ_i = inherent cohesive joint strength;

τ_n = joint shearing stress;

σ_n = joint normal stress;

$F = \tan^{-1} \phi$ = joint friction factor - extrapolated from last three slips with a parabolic curve fit.

3.3.5 Test Results

Table 3.4 presents the results of the room-temperature and heated triaxial joint tests.

3.3.6 Test Data Analysis

The slip factors for each sample show very good consistency and exhibit the classical decrease with successive slips as the joint surface becomes increasingly polished. Joint strength can be expected to vary widely from joint to joint and, as such, is difficult to apply analytically. The friction behavior of a failed joint, however, can be fairly well characterized and applied in analyses. The results so far seem to be defining a range of useful friction factors.

TABLE 3.4

INHERENT JOINT STRENGTHS AND SLIP FACTORS FOR JOINTED SAMPLES

UNHEATED TRIAXIAL JOINTS

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(g/cc)</u>	<u>APPARENT SLIP FACTORS</u> ($\Delta \tau_n / \sigma_n$)				<u>JOINT</u> <u>STRENGTH</u> <u>(psi)</u>
			<u>1 ksi</u>	<u>2 ksi</u>	<u>3 ksi</u>	<u>5 ksi</u>	
3058.5	TJ1	2.44	.821	-	-	-	-
3182.6	TJ6	2.74 saturated	3.029	2.152	1.934	1.617	4021
3251.1	TJ7	2.83 saturated	.685	.630	.633	.627	2030
3251.3	TJ8	2.84	.966	.929	.867	-	1065
3257.0	TJ10	2.68	.937	.834	.817	.781	693

HEATED TRIAXIAL JOINTS

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(g/cc)</u>	<u>APPARENT SLIP FACTOR</u> ($\Delta \tau_n / \sigma_n$)				<u>JOINT</u> <u>STRENGTH</u> <u>(psi)</u>
			<u>20°C</u>	<u>150°C</u>	<u>300°C</u>	<u>500°C</u>	
3128.9	TJ2	2.75	.674	.678	.689	.688	0
3141.8	TJ3	2.51	2.102	2.062	1.815	1.307	203
3180.1	TJ5	2.69	1.690	COMPLETE FAILURE OF SAMPLE			

Hold Pt.

Hold Pt.

The effect of temperature on joint behavior is inconclusive at this time. However, through single observation, it would appear as if sample TJ2 had its joint slip resistance increased as a result of heating, since the slip factor does not show the characteristic fall-off with the number of slips. Sample TJ3 does show the characteristic fall-off with temperature and it would be hard to determine if any of the fall-off was due to temperature.

3.4 MEASUREMENT OF THE THERMAL PROPERTIES OF INTACT CORE UNDER VARYING AMBIENT CONDITIONS

3.4.1 Thermal Conductivity/Specific Heat Procedures

3.4.1.1 Apparatus

The thermal properties tester is enclosed by a 10-in. diameter by 18-in. high-vacuum bell jar in a wire cage, and sealed and supported at the bottom by a massive aluminum base with feed-throughs for vacuum, hydraulic pressure, thermocouple wires, and electrical power. Inside the tester is a loading frame enclosing the instrumented test stack. The frame consists of 1-1/2-in. thick square steel plates on top and bottom, held together by four 1-in. diameter stainless steel threaded rods. Inside the loading frame, from top to bottom are: a stainless steel flatjack rated at 5000 psi at 600°C; a 1-in.-thick ceramic (insulating) platen; a conical heater on a stainless steel form, providing a 5:1 area reduction from the flatjack to the sample (and a corresponding 5:1 increase in pressure); the sample test stack, consisting of 2 pyrex reference discs of well-known thermal properties the same size and shape as the sample; bracketing the sample, with 5 thermocouples in very thin aluminum discs, 1 at each disc interface and 1 drilled into the sample; and, finally, a second conical heater identical to the top, but containing an integral spherical seat to ensure uniform loading.

The data are recorded on a strip chart (time base) recorder as the outputs of the five thermocouples and hydraulic pressure to the flatjack (from an internal pressure transducer) versus time. The data are multiplexed on the single pen recorder via an Omega Engineering "Dataplex 10" signal scanner and pen lift.

The heating rates are controlled by Weathermeasure temperature controllers with controlling thermocouples placed in series opposed to a millivolt ramp generator.

3.4.1.2 Test Specimens

Test specimens were 5/8-in. thick sections of core (right circular cylinders) approximately 2 in. in diameter. The faces were ground flat and parallel to within 0.0001 in. This specification was important, because a slight irregularity on the surface will cause point loading and shattering of the pyrex.

3.4.1.3 Procedures

Before each test, the spherical seat was tested for freedom of motion and lubricated with molybdenum grease if deemed necessary. The bolts on top of the loading frame were loosened and the sample was inserted into its correct position. The thermocouples (of very thin wire) were checked for correct placement and the bolts atop the frame were tightened to secure the stack. Radiant heat shields of polished steel were placed around the test stack, the bell jar was positioned, and the system pressure was reduced.

At this point, the test was initiated. The flatjack was pressurized via a hand pump to 1/5 the desired stress on the sample. Then the temperature controller inputs were balanced, the ramp generator was started, and heating begun. The test stack was heated from both ends simultaneously at a rate of about 3°C per minute. Previous experiments have shown this heating rate to give the most consistent results. The dataplex unit operates to scan the hydraulic pressure and 5 thermocouples sequentially, and prints them as dashed lines on the strip chart recorder. Heating continued at a constant rate until the desired sample temperature was reached, at which time the ramp generator, heaters, and chart recorder were de-energized, air was admitted, and the test was concluded.

3.4.1.4 Calculation

Our system was designed to minimize convective and radiant heat transfer from the test stack by operating in a vacuum (10^{-4} mm. mercury pressure) and by surrounding the stack with a highly reflective radiant heat shield. Thus, the system was idealized as a transient, one-dimensional conduction system with varying thermal properties.

This system was also used at Colorado State University in a similar setup. They were able to reduce Carslaw and Jaeger's equations to the simple set of formulae used in our calculations:

$$\alpha = \frac{L^2 V}{4 (T_2 + T_4) - 8T_3} \quad (7)$$

$$C_p = \frac{K'}{\rho LV} \frac{T_1 - T_2 + T_5 - T_4}{L} - .965 \frac{V' L'}{\alpha'} \quad (8)$$

$$K = \rho C_p \alpha \quad (9)$$

where

α = thermal diffusivity of sample;

C_p = specific heat of sample;

K = thermal conductivity of sample;

T_1 = temperature at lower reference-heater interface;

T_2 = temperature at lower reference-sample interface;

T_3 = temperature at upper reference-sample interface;

T_4 = temperature at upper reference-heater interface;

T_5 = temperature at center of sample;

L = thickness of sample;

V = heating rate of sample ($= T_5$);

ρ = density of sample;

K' = thermal conductivity of pyrex references;

L' = thickness of pyrex references;

α' = thermal diffusivity of pyrex references;

V' = heating rate of pyrex references $(= \frac{T_1^0 + T_2^0 + T_3^0 + T_4^0}{4})$.

3.4.2 Thermal Expansion

3.4.2.1 Apparatus

The equipment used for the thermal expansion determinations consists of a high-temperature dilatometer designed to use a vacuum and capable of continuously monitoring sample deformation with temperature. The unit is fully compensated for device-related deformations and has a programmable temperature control feature.

3.4.2.2 Test Specimens

Test specimens were 1/4-in. in diameter and had a length of approximately 1.2 in. The ends were ground flat and parallel to within 0.001 in. The length was determined to within 0.001 in.

3.4.2.3 Procedures

Prior to each series of tests, a specimen with a known coefficient of expansion was inserted in the dilatometer and heated over the test range to check unit operation. Then the sample of basalt was placed in the device, making sure all contacts were clean and that the quartz probe moved freely. The thermocouples were then brought in contact with the specimen and the vacuum capsule slid over the holder and probe. The vacuum pump was then started and heating begun. Sample temperature and thermal expansion were continuously recorded over the range of 20°C to the desired upper temperature.

3.4.2.4 Calculation

The coefficient of thermal expansion was then calculated:

$$\alpha_T = \Delta_L / L / \Delta_T \quad (10)$$

where

α_T = coefficient of thermal expansion;

Δ_T = change in temperature;

ΔL = change in length for temperature change, Δ_T ;

L = length of sample.

3.4.2.5 Test Results

The results of the thermal expansion tests are presented as a function of depth in Table 3.5.

TABLE 3.5

THERMAL EXPANSION COEFFICIENTS

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(g/cc)</u>	<u>TEMP. RANGE</u> <u>(°C)</u>	<u>EXPANSION COEFFICIENT</u> <u>($\times 10^{-6}$ in/in - °C)</u>
3148.8	XP 7	2.63	23-572	7.37
3163.9	XP 9	2.79	25-393	10.77
3182.9	XP 4	2.66	64-640	8.04
3253.0	XP 5	2.57	25-508	11.16
3256.3	XP11	2.49	20-546	10.48
3256.3	XP12	2.49	20-576	10.11
3256.3	XP12 (saturated)	2.49	18-548	11.00

3.4.2.6 Test Data Analysis

The thermal expansion results were quite consistent over the central section of the basalt flow. It was not possible to get a small core from the clastic upper flow area due to fracturing problems.

The thermal expansion was fairly linear over the range tested, but some very interesting variations did occur for several of the samples. An initial "knee" occurred for all samples of basalt at from 90-130°C, but did not occur for the calibration sample. Since this "knee" occurs near the vaporization point of water, it is possible that this may signify a change of state of some dehydrated minerals. It probably cannot be simple dehydration, as the "knee" reappeared when a sample was rerun. Another perturbation occurred on some samples at a higher temperature, approximately 400°C, where the thermal expansion would approach zero for a period, even though heating continued. No such behavior was noted for the calibration runs. In addition, when the samples were rerun, the transient variation in thermal expansion no longer occurred. These observations lead to the conclusion that possibly

there is a change of state occurring in the samples at elevated temperatures which causes the temporary deviation in thermal expansion from linear. If this is the case, the transformation is permanent, as the perturbation does not repeat upon rerunning the sample. A copy of the recorder output showing the two perturbations is included as Figure 3.9 and a rerun of the same sample as Figure 3.10.

Figure 3.9: Initial Expansion Run with "Knee"

Figure 3.10: Repeat Expansion Run Without "Knee"

3.5 CREEP TESTS

3.5.1 Apparatus

The apparatus used consisted of Soiltest CT-710 series compression testing machines and heater jackets for the high-temperature tests.

Deformations were recorded by dial gages.

3.5.2 Test Specimens

Test specimens were right circular cylinders within tolerances specified in ASTM D-2938. The length was as close to 2 times the diameter as possible (except that shorter samples were required in these highly fractured cores). Exception was also taken to the ASTM D-2938 requirement for NX core (2-1/8 in. diameter), as the core for this contract is smaller in diameter (1-7/8 in.). The samples were oven dried overnight at 90°C where required. The diameter and length were determined to within 0.01 in. and the weight measured to 0.1 gram. For the tests at high temperatures, the samples were heated overnight at the desired temperature prior to testing.

3.5.3 Procedures

The sample, with heater jacket when required, was inserted into the compression tester and a steady-state thermal situation established at the desired temperature. The required constant load was then applied to the specimen. Initial deformation readings were then taken. Deformations were continuously monitored at least daily, and the load and temperature maintained until a steady-state creep rate was attained. Ambient room temperature was recorded at each displacement monitoring.

3.5.4 Calculation

The creep rate was continuously calculated by dividing the increase in strain by the time over which it occurs.

3.6 ROCK HARDNESS

3.6.1 Apparatus

Scleroscope hardness tester.

3.6.2 Test Specimens

Spare sections of core and unbroken thermal samples were used for hardness tests. A polished surface was used for the tests.

3.6.3 Procedures

Ten or more indentations were made using the scleroscope tester, and the results averaged to determine a rock hardness.

3.6.4 Calculation

The scleroscope hardness number was read directly from the machine, on a scale of 0-100, with 100 being an average value for hardened steel.

3.6.5 Test Results

A scleroscope rock hardness test was performed on ten samples of basalt from along the length of the supplied core. The results of those tests as a function of depth are provided in Table 3.6.

TABLE 3.6

SCLEROSCOPE HARDNESS COEFFICIENTS

<u>DEPTH</u> <u>(ft)</u>	<u>SAMPLE</u> <u>NUMBER</u>	<u>DENSITY</u> <u>(gm/cc)</u>	<u>HARDNESS</u>	
			<u>Mean</u>	<u>Std. Dev.</u>
3043.9	KP 1	2.23	20.3	7.0
3051.8	KP 4	2.20	23.4	11.4
3053.5	KP 2	2.24	17.5	12.3
3128.6	K 6	2.81	57.3	10.2
3129.4	KP 3	2.75	40.9	7.9
3143.1	K 8	2.64	62.0	6.9
3183.5	K 11	2.79	69.8	8.2
3253.0	XP 5	2.57	45.7	5.0
3257.2	K 14	2.52	36.0	6.7
3257.4	K 13	2.18	48.7	14.7

3.6.6 Test Data Analysis

As would be expected, there was a wide variation in average rock hardness between samples, and a high standard deviation within samples. The value of hardness on an absolute scale is questionable, but it provides a reasonable means for comparing hardness over a range of basalt thicknesses and to similar rock types.

Scleroscope hardness is plotted versus depth of core in Figure 3.11. Hardness appears to correlate fairly well with depth. One can even imagine a domed curve through the points indicating a lower hardness near the top of the flow, increasing hardness as the center of the flow is approached, and then a fall-off of hardness toward the bottom of the flow.

Figure 3.11: Scleroscope Hardness Versus Depth of Core

3.7 INVESTIGATION OF ANISOTROPY OF A SELECTED BASALT SAMPLE

3.7.1 Apparatus

The equipment used for the dynamic wave velocities determinations consisted of:

1. 0.5-megahertz (MHz) driver and pick-up longitudinal wave crystals manufactured by Panametrics;
2. 0.5-MHz driver and pick-up shear wave crystals manufactured by Panametrics;
3. Tektronix FG 502 function generator;
4. Two Tektronix PG 501 pulse generators;
5. Tektronix AM 501 operational amplifier;
6. Tektronix DC 503 universal counter;
7. Tektronix 465 100-MHz dual trace oscilloscope;
8. 4-, 6-, 12-, and 18-in. aluminum calibration bars;
9. Ancillary leads and connectors.

3.7.2 Test Specimens

The test specimens were the uniaxial and triaxial compression test specimens. Tolerances were well within those specified in ASTM D-2845.

3.7.3 Procedures

Prior to each series of tests, the aluminum calibration bars were tested for both P and S wave velocity to determine if all equipment was working satisfactorily. Then the ends of the sample were carefully cleaned and a couplant jelly applied. The respective longitudinal or shear wave crystals were applied to the ends of the sample with uniform pressures and centered. A single cycle sine wave of the desired frequency (0.5 MHz for free medium P and S wave tests, 5 kilohertz (KHz) for bar velocity determinations) were pulsed through the sample, and the travel time determined from the scope and counter.

Corrections for transducer and couplant thicknesses were determined from the tests on different length aluminum bars. The procedure was then repeated across the diameter of the specimen.

In addition, high-temperature transducers were installed in the platens of the triaxial compression apparatus, and wave velocities continuously monitored during testing.

3.7.4 Calculation

The compression and shear wave velocities were then calculated from:

$$V_p = L_p / T_p \quad (11)$$

$$V_s = L_s / T_s \quad (12)$$

where

V_p = longitudinal wave velocity;
 V_s = shear wave velocity;
 L_p = L_s = length or diameter of specimen;
 T_p = travel time for longitudinal wave;
 T_s = travel time for shear wave.

3.7.5 Test Results

Since an early modification of the contract eliminated the continuous monitoring of acoustic wave velocities from the testing program, the only method available to find a sample displaying anisotropic acoustic behavior was to measure axial and radial P and S wave velocities on all the compression samples. This was done, and the results of that survey are compile in Table 3.7 by depth.

3.7.6 Test Data Analysis

Shown in Table 3.7, along with recorded longitudinal and shear wave velocities, is the ratio of the respective wave velocities in the axial

TABLE 3.7

DYNAMIC WAVE VELOCITIES AND RATIOS IN AXIAL AND RADIAL DIRECTIONS

DEPTH (ft)	SAMPLE NUMBER	V_p^{ax} (m/s)	V_p^{rad} (m/s)	$\frac{V_p^{ax}}{V_p^{rad}}$	V_s^{ax} (m/s)	V_s^{rad} (m/s)	$\frac{V_s^{ax}}{V_s^{rad}}$
3036.2	UC 1	2704	ND	ND	1982	ND	ND
3036.3	TX 1	3379	ND	ND	2540	ND	ND
3036.5	U 2	3194	ND	ND	2124	ND	ND
3043.6	UC 2	2626	2716	0.97	1974	1781	1.11
3043.8	U 3	3077	2693	1.14	2193	1808	1.21
3051.7	TX 4	2734	3226	0.85	1774	1934	0.92
3052.5	U 4	3685	3355	1.10	2203	2060	1.07
3052.7	TX 5	3079	2540	1.21	2060	1606	1.28
3053.0	TX 6	3031	2557	1.19	2069	1934	1.07
3053.2	TX 31	3024	2067	1.46	2300	1781	1.29
3053.4	U 5	3078	3018	1.02	2016	1680	1.20
3055.0	TX 7	3173	ND	ND	2942	ND	ND
3058.5	TJ 1	3172	3806	0.83	1990	2153	0.92
3058.7	TX 8	3416	ND	ND	2311	ND	ND
3128.7	TX 9	5549	ND	ND	3283	ND	ND
3128.9	TJ 2	5455	5518	0.99	2915	3226	0.90
3129.1	U 7	5602	6075	0.92	3122	3408	0.92
3131.0	PF 1	5422	5765	0.94	3810	3024	1.26
3131.3	TX 10	5670	3073	1.85	3305	3154	1.05
3131.7	U 8	5523	4279	1.29	3183	3902	0.82
3131.9	PF 2	5334	ND	ND	3247	ND	ND
3138.3	U 9	5493	4921	1.12	3005	3506	0.86

TABLE 3.7 (Cont'd)

DEPTH (ft)	SAMPLE NUMBER	V_p^{ax} (m/s)	V_p^{rad} (m/s)	$\frac{V_p^{ax}}{V_p^{rad}}$	V_s^{ax} (m/s)	V_s^{rad} (m/s)	$\frac{V_s^{ax}}{V_s^{rad}}$
3139.1	TX 12	5559	5145	1.08	3183	3043	1.05
3139.3	U 21	5380	5438	0.99	2987	3163	0.94
3141.6	U 10	5556	5147	1.08	3226	2766	1.17
3141.8	TJ 3	5784	ND	ND	3032	ND	ND
3142.2	TX 13	4956	7764	0.64	3323	3071	1.08
3142.4	UC 6	2166	2357	0.92	4522	2251	2.01
3143.5	UC 7	5329	2308	2.31	2940	ND	ND
3143.8	TX 15	5744	5877	0.98	3323	1457	2.28
3147.7	U 11	5248	5192	1.01	3043	3062	0.99
3148.0	TX 16	5413	4837	1.12	3465	3071	1.13
3148.2	TJ 4	5386	4989	1.08	3209	3107	1.03
3148.5	U 12	5686	5363	1.06	3292	3102	1.06
3148.7	U 22	5349	5288	1.01	3247	3163	1.03
3148.9	TX 17	5787	ND	ND	3369	ND	ND
3163.7	TX 18	5876	5671	1.04	3209	3006	1.07
3163.9	UC 9	5478	ND	1	3045	ND	ND
3164.1	U 13	5693	5437	1.05	3158	3137	1.01
3164.5	TX 19	5761	5430	1.06	3332	3176	1.05
3164.7	UC 10	5390	4500	1.20	3201	3017	1.06
3165.0	U 14	5722	5591	1.02	3117	3096	1.01
3166.1	TX 20	5192	4724	1.10	3644	3616	1.01
3166.3	TX 32	5165	2626	1.97	3433	3158	1.09
3166.5	U 15	5808	5538	1.05	3290	3223	1.02

TABLE 3.7 (Cont'd)

DEPTH (ft)	SAMPLE NUMBER	$V_{p \text{ ax}}$ (m/s)	$V_{p \text{ rad}}$ (m/s)	$\frac{V_{p \text{ ax}}}{V_{p \text{ rad}}}$	$V_{s \text{ ax}}$ (m/s)	$V_{s \text{ rad}}$ (m/s)	$\frac{V_{s \text{ ax}}}{V_{s \text{ rad}}}$
3169.1	U 16	5468	4842	1.13	3201	3137	1.02
3179.6	U 17	5780	4954	1.17	3354	3196	1.05
3179.8	TX 33	5759	2934	1.93	3104	3006	1.03
3180.0	TX 22	5328	4931	1.08	2778	3045	0.91
3180.1	TJ 5	5744	5676	1.01	3162	3121	1.01
3182.6	TJ 6	5545	4942	1.12	3209	3146	1.02
3183.4	U 18	5751	5622	1.02	3158	3137	1.01
3183.7	TX 23	5683	ND	ND	3467	ND	ND
3183.9	UC 13	5331	ND	ND	4798	ND	ND
3248.7	TX 24	3110	5217	0.60	2915	3064	0.95
3251.1	TJ 7	5255	4864	1.08	3265	3137	1.04
3251.2	TJ 8	5519	4807	1.15	3240	3014	1.08
3251.4	TX 25	5703	5769	0.99	3226	3293	0.98
3251.7	TX 34	6909	5314	1.30	3061	3271	0.94
3251.9	TX 26	5522	5522	1.00	4182	3157	1.32
3252.1	U 19	5532	5532	1.00	3058	3118	0.98
3252.7	TJ 9	5497	6374	0.86	2465	2976	0.83
3257.0	TJ 10	4421	4297	1.03	3375	2812	1.20
3257.3	TX 27	3644	3644	1.00	2253	2076	1.09
3261.2	TX 29	3322	3322	1.00	2267	2096	1.08
3261.4	UC 15	3204	2777	1.15	2461	2197	1.12
3261.6	TX 30	3232	3209	1.01	2520	2203	1.14
3261.8	U 20	3387	3361	0.98	2369	2143	1.11

RHO-BWT-C-50

direction of the core to the velocity in the radial direction. Generally, a deviation of this ratio from 1.0 of over 10 percent is considered an indication of anisotropy. Overall, there were not many samples that deviated over 10 percent, indicating essentially isotropic elastic conditions within the basalt. Requiring a 10 percent variation in both the longitudinal and shear wave velocities further restricts the candidates for investigation of anisotropy. Those samples which did indicate anisotropic behavior have been sent for further characterization to determine the probable cause of the observed anisotropy.

As an indication of how the velocity varies with depth, the axial and radial P wave velocities are plotted in Figure 3.12. Variation with position in the flow is evident, with the same indication of low modulus near the top of the flow, increasing modulus at the center, and then decreasing near the bottom of the flow, as was observed for the hardness tests.

Figure 3.12: P Wave Velocity Versus Depth

3.8 POST-FAILURE CHARACTERISTICS OF BASALT CORES

3.8.1 Apparatus

The apparatus was the same as used for the uniaxial and triaxial testing, with the addition of steel stiffeners in parallel with the sample.

3.8.2 Test Specimens

Test specimens were right circular cylinders within tolerances specified in ASTM D-2938. The length was as close to 2 times the diameter as possible (except that shorter samples were required in these highly fractured cores). Exception was also taken to the ASTM D-2938 requirement for NX core (2-1/8-in. diameter), as most of the core for this contract was smaller in diameter (1-7/8-in.). The samples were oven dried overnight at 90°C, where required. The diameter and length were determined to within 0.01 in. and the weight measured to 0.1 gram. For the tests at high temperatures, the samples were heated overnight at the desired temperature prior to testing.

3.8.3 Procedures

Before each test, the calibration of the load cell and displacement transducers was checked. The stiffening frame was placed on the testing machine and the sample locked between the upper and lower plates. The stiffening frame was then loaded at a uniform rate which in turn loads the sample. The sample load was measured by a load cell in series with the sample inside the stiffener and displacements were measured by direct current displacement transducers. The complete load versus deformation curve was recorded, including the post-failure behavior, until the residual strength was reached.

3.8.4 Calculation

The post-failure strength at any point was calculated by dividing the load at that point by the sample cross-sectional area.

3.8.5 Test Results

Two post-failure tests were run, one at room temperature and pressure and one at high pressure. A third planned test at high temperature must wait for the arrival of more samples.

The first tests, at room temperature and pressure, were not able to be controlled in the post-failure region, even with the added stiffeners.

The second test at high pressure was even more difficult. Initially, 5000 psi confining pressure was used, and the machine was unable to break the rock by the time 1 million pounds were on the stiffening frame (200,000 pounds on sample). Realizing an exceptionally strong rock had been chosen, the confining stress was reduced to 2500 psi and the test repeated. Again, the machine was unable to break the sample. The confining pressure was finally lowered to 1000 psi and failure took place. However, since the sample was so strong, very little capacity was left on the testing machine and only a small portion of the post-failure curve was obtained.

Results obtained during the two tests are plotted in Figures 3.13 and 3.14, respectively.

3.8.6 Test Data Analysis

As expected, obtaining post-failure behavior on a brittle high-strength material like basalt was quite difficult. In the future, it will probably be necessary to select weaker samples for post-failure analysis so that sufficient capacity remains in the testing machine to allow a complete post-failure analysis.

The successful control of failure initiation demonstrated in Figure 3.14 indicates that post-failure control can be accomplished, at least on a confined sample. Work will continue on perfecting the test.

Figure 3.13: Room Temperature Post-Failure Test Graph

Figure 3.14: Triaxially Confined Post-Failure Test Graph

3.9 PHYSICAL PROPERTIES

3.9.1 Apparatus

The apparatus used for the density determinations consists of an analytical balance and precision micrometer calipers.

3.9.2 Test Specimens

Test specimens were cored and ground to approximately 3/4 in. diameter by 1-in. length. This size was selected to facilitate compression testing and precision weighing. Obvious anomalies such as vesicles or fractures are avoided.

3.9.3 Procedures

The prepared sample is dried for 24 hours at 105°C and weighed on a balance to within 0.1 gram. Length and diameter are measured to within 0.001 in.

3.9.4 Calculation

The bulk density was determined as follows:

$$\rho_B = \frac{M_D}{\frac{\pi}{4} L D^2} \quad (13)$$

where

ρ_B = bulk density;

M_D = mass of dried sample;

L = sample length;

D = sample diameter.

The apparent grain density can be determined by subtracting pore volume (determined from the porosity test) from the total volume of the sample.

3.9.5 Test Results

The determined bulk density for each of the tested samples is provided in the results section under the appropriate tests. It should be noted that a

true density measurement was often quite difficult due to the fractured nature of the supplied core.

3.9.6 Test Data Analysis

Bulk densities recorded were generally quite consistent for contiguous segments of core. Lowest densities were recorded for the upper portion of the flow, the highest in the central portions of the flow, and again, a decrease in density toward the bottom of the flow. As discussed in previous sections, density correlated well with many of the physical properties of the basalt. Density should be very useful as a preliminary gage of expected properties.

4.0 GENERAL DISCUSSION

4.1 COMPARISON TO FISCAL YEAR 1978 RESULTS

In overiewing the results of the current tests on deep basalts and last year's tests of near-surface basalts, there appears to be a generally very good correlation between the two. Compressive strength, Young's modulus, and Poisson's ratio are all in the same range with similar intra-group variations. Based on the limited current information, joint strength properties are similar between the two investigations, with the earlier near-surface basalts appearing to have slightly higher coefficients of joint friction. More data on the deep basalts will be required, however, before that conclusion can be validated. Thermal expansion values do appear to be significantly higher for the deep basalts, but both groups had similar maximums. Less anisotropy was evidenced in the acoustics for the deep basalts, even with its more prevalent jointing. Some of this effect may be due to our own improvement in equipment and technique in determining wave velocities. Densities and variations in densities were comparable. Variations in properties with density, and consequently the relative position in the flow, showed the same trends from the top of the flow to the bottom.

4.2 LIMITATIONS OF SAMPLES, PROCEDURES, AND RESULTS

The primary limitation to the current study is the reduced number of samples with which we were provided. Unlike last year, when we could carefully select samples having the desired jointing and length characteristics, we were forced to obtain samples from every possible segment of core. Compressive sample lengths had to be reduced by half, waiving the ASTM requirement, and samples broken in coring, handling, or preparation had to be used (often patched with hydrostone or epoxied together from fragments)

to perform the contracted number of tests. Thus, measured strengths may be higher than actual (in situ) strengths in many cases. The steps necessary to prepare the sample are noted on the data sheets.

The procedures are acceptable given the qualitative nature of the study to date. When the site is chosen, a more detailed and thorough test program should be undertaken to raise confidence levels in the generality and applicability of the data.

As discussed earlier, several factors limit the quantitative application of the data at this time. These include: the very limited amount of core supplied from which to select samples; the necessity of using reduced-size samples; the unavailability of mitigating physical features, like chips, open joints, and voids within the samples; and the lack of sufficient replication for establishing confidence levels for various effects. It is hoped that the additional replications will confirm some of the results as the next two series of tests are completed.

5.0 CONCLUSIONS

The most significant conclusions to be made from the present set of tests are:

1. There is agreement between the results of the current investigation and last year's results; for example, the uniaxial compressive strength (ksi) at room temperature was 22.97 ± 14.78 for last year;
2. Temperatures of 500°C appear to reduce the compressive strength by approximately 50 percent compared with results at room temperature (see Tables 3.2 and 3.3);
3. Density was found to correlate well with compressive strength and other elastic properties; as the rock density increases, the compressive strength and other elastic properties also increase;
4. Increasing the confining pressure from 0 to 3000 psi will increase the compressive strength by 50 to 100 percent (see Figures 3.5, 3.6, and 3.7).

Variation in the rock density and the large number of different tests makes it difficult to conclude much statistically at this time; we have insufficient samples. Further investigations on the Series B and C cores will lead to more conclusive statements.

Some areas which suggest possible trends are as follows:

1. Acoustic velocities are effective in characterizing the elastic properties of basalt, but may be limited in application over distance due to the transmission-interfering effects of joints; anisotropy was less evident for these deep cores than the cores tested in 1978;

2. Thermal expansion is significantly higher than measured for the basalt tested in 1978; a consistent non-linearity at 100-150°C was noted that did not show up in the 1978 testing or in the calibration samples; this may be due to de-watering, but has not been conclusively explained.

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